Final results from the CUPID-Mo $0\nu\beta\beta$ experiment

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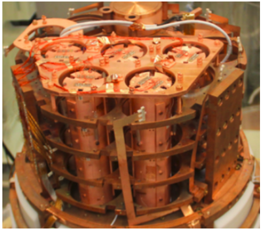
GDR DUPhy November 2021

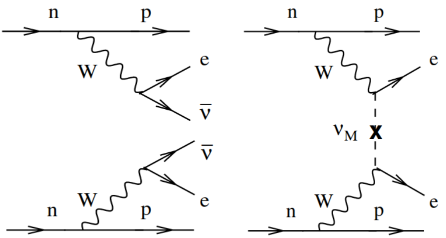


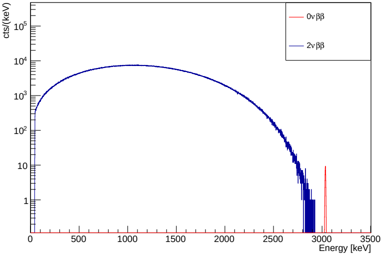
$0\nu\beta\beta$ decay

- Two-neutrino double beta decay ($2\nu\beta\beta$) rare SM process
- Can occur if single beta decay energetically forbidden [1]

$$2n \rightarrow 2p + 2e^{-} + 2\bar{\nu_e} \tag{1}$$

- If neutrino is Majorana particle, could get the decay without neutrinos
- Neutrinoless double beta decay ($0\nu\beta\beta$) would not conserve Lepton number leading to beyond standard model physics
- Full decay energy carried by nucleus and 2 electrons
- Leads to clean experimental signature, total energy at $Q_{\beta\beta}$

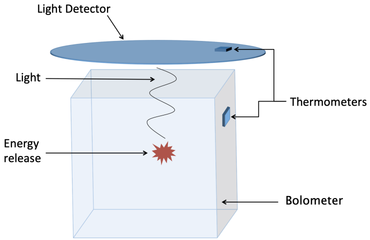


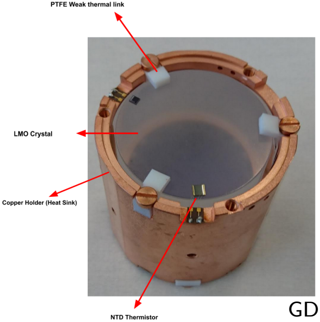


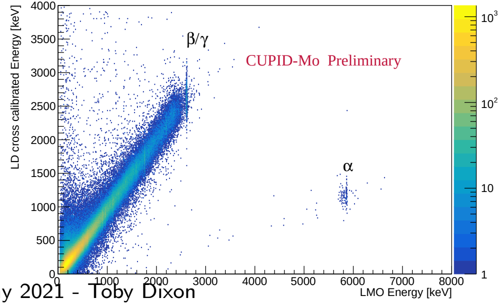
[1]Or strongly suppressed

Cryogenic calorimeters (bolometers)

- $Li_2^{100}MoO_4$ (LMO) crystals cooled to $10-20\ \mathrm{mK}$, instrumented with NTD-Ge thermistors
- Particle deposits cause an increase in temperature
- Bias on NTD causes this to be registered as a pulse in voltage
- CUPID-Mo also employs a second bolometer as a light detector for $\gamma(\beta)/\alpha$ particle ID
- Scintillation light different for β/γ and α, allowing particle ID



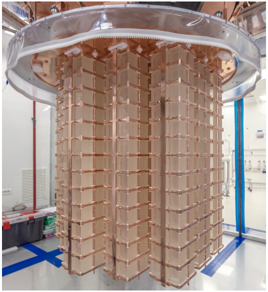


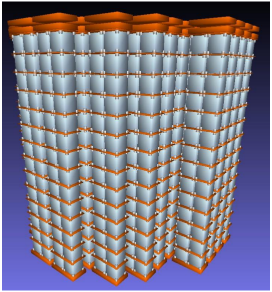


From CUORE to CUPID

- **CUORE** is a current leading $0\nu\beta\beta$ experiment
- 988 TeO_2 bolometers
- First tonne-scale solid state $0\nu\beta\beta$ experiment
- World leading limit on $0\nu\beta\beta$ in ^{130}Te
- Sensitivity limited by high background from from α particles

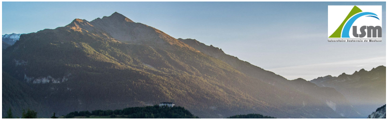
- **CUPID** is a planned experiment
- Use scintillating bolometers with light detectors to remove α background
- Non scintillating to scintillating crystal, $TeO_2 \rightarrow Li_2MoO_4$
- ^{100}Mo higher Q-value means lower γ background
- Enriched crystals $\implies$ more target nuclei

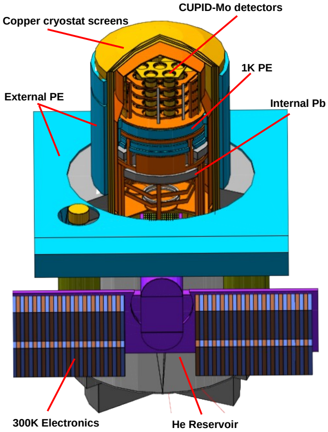




The CUPID-Mo experiment

- CUPID-Mo demonstrated the use of Lithium Molbydate (LMO) scintillating calorimeters for CUPID [2]
- Operated successfully between 2019-2020 in EDELWEISS cryostat, LSM France
- Consisted of 20 $Li_2^{100}MoO_4$ (LMO) crystals ($\sim$ 200 g) and 20 Ge light detectors (LD)



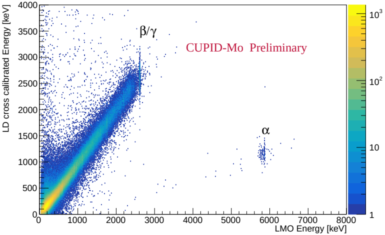


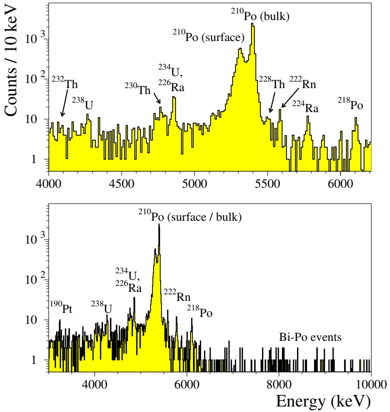
Geant4 rendering of the CUPID-Mo detectors in the EDELWEISS set-up

[2]https://arxiv.org/abs/1909.02994

CUPID-Mo performance

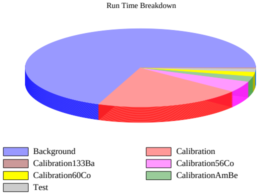
- Primary aim of CUPID-Mo to demonstrate performance for CUPID
  - **Particle ID**: Full ($> 99.9\%$) α rejection
  - **Energy resolution** of LMO calorimeters (~ 7 keV FWHM at $Q_{\beta\beta}$)
  - **Crystal radio-purity**: ($< 1\ \mu\mathrm{Bq/kg}$ activity for ^{238}U/ ^{232}Th)

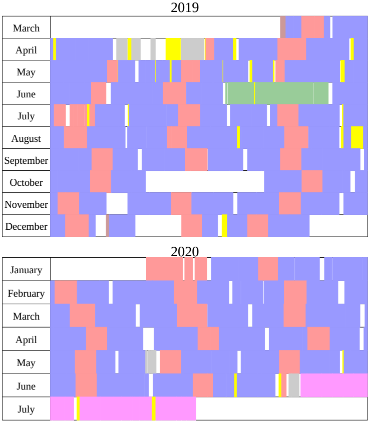




CUPID-Mo $0\nu\beta\beta$ analysis

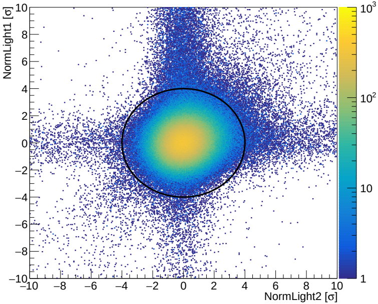
- We used the full collected CUPID-Mo data to search for $0\nu\beta\beta$
- Data collected between March 2019 and June 2020
- New data analysis: Improved LY, muon veto, PSD cuts and detector coincidences.
- Exposure of 1.47 kg-yr of ^{100}Mo





Data selection cuts

- CUPID-Mo strategy to reduce backgrounds:
  - **Single crystal cut** - reduce external γ background
  - **Pulse-Shape discrimination cuts** - remove pileup/ non-physical events using PCA method[3]
  - **Light Yield cuts** - remove the α background, cuts modified to use normalised light energies and 2D cut
  - **Muon veto** - remove muon induced events
  - **Delayed coincidences** - remove events from ^{232}Th decay chain and a novel cut for ^{238}U decay chain



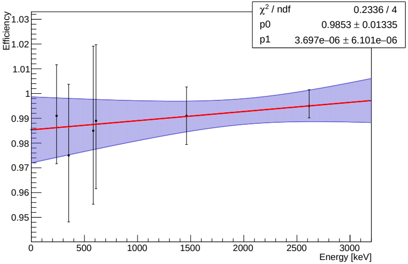
$$^{222}\text{Rn} \xrightarrow[\alpha(5590\ \text{keV})]{3.8\ \text{day}} {}^{218}\text{Po} \xrightarrow[\alpha(6115\ \text{keV})]{3.1\ \text{min}} {}^{214}\text{Pb} \xrightarrow[\beta^-(1019\ \text{keV})]{26.8\ \text{min}} {}^{214}\text{Bi} \xrightarrow[\beta^-(3267\ \text{keV})]{19.9\ \text{min}} {}^{210}\text{Pb}$$

[3] https://arxiv.org/abs/2010.04033

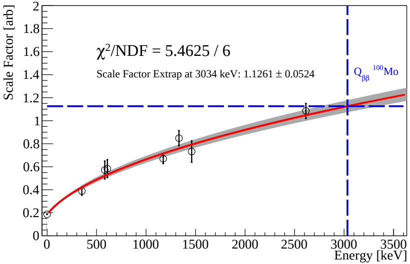
Efficiency, energy resolution

- **Efficiencies**
- Efficiencies estimated for each cut
- Use random triggers, ^{210}Po events and γ peaks for LY and PSD cuts
- Efficiency extrapolated to $Q_{\beta\beta}$
- Total efficiency of 88.4 ± 1.8 %

- **Energy resolution**
- Estimate energy resolution for $0\nu\beta\beta$ analysis
- Construct lineshape function from fit to 2615 keV in calibration data
- Scale this to $Q_{\beta\beta}$ using fits of physics data peak



LY cut efficiency



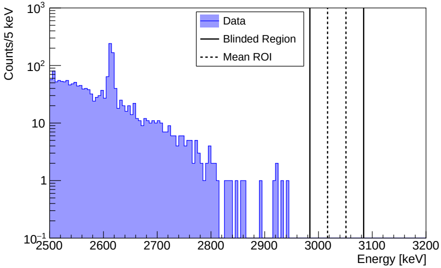
Resolution scale factor

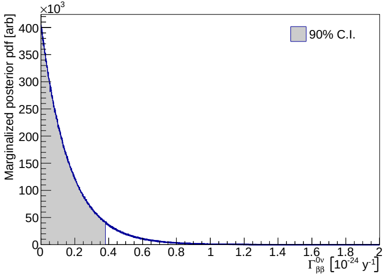
$0\nu\beta\beta$ limit

- After unblinding no events observed in ROI
- Bayesian counting analysis leads to:

$$\boxed{T_{1/2} > 1.8 \times 10^{24} \text{ yrs } 90\% \text{ CI}}. \quad (2)$$

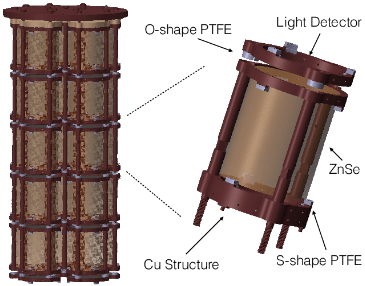
- Including all systematics
- New world leading limit for ^{100}Mo
- Achieved with ~ 2 orders of magnitude lower exposure (1.47 kg-yr of ^{100}Mo) than other leading experiments

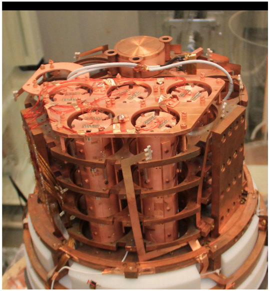




Combined CUPID-demonstrators limit

- CUPID-0 another CUPID demonstrator
- Used $Zn^{82}Se$ bolometers operated in LNGS
- Combine the two experiments to get limit on $\langle m_{\beta\beta} \rangle$ with light Majorana neutrino exchange model
- Demonstrate advantage of multi-isotope experiment (reduced theoretical uncertainty)





Combined CUPID-demonstrators limit

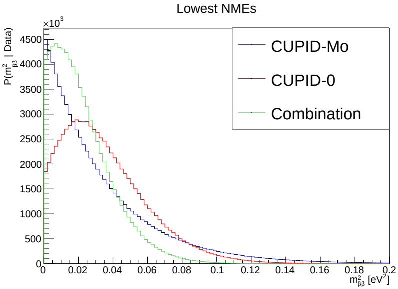
- Bayesian analysis treating the NMEs as nuisance parameters

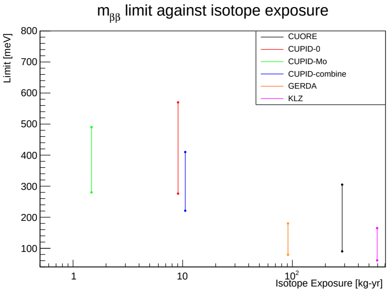
$$(T_i^{0\nu})^{-1} = (G \cdot g_A^4)_i |M_i^{0\nu}|^2 m_{\beta\beta}^2 / m_e^2$$

- Combine limits directly with Bayes thereom for worst case and best case NME
- Flat prior on $\langle m_{\beta\beta}^2 \rangle$

- Combined limit approaches results of experiments with orders of magnitude higher exposure

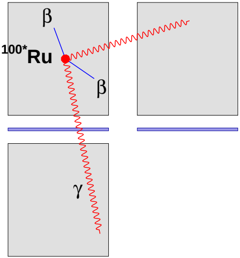
Experiment	$m_{\beta\beta}$ limit [meV]
CUPID-Mo	280 – 490
CUPID-0	280 – 570
Combination	220 – 410

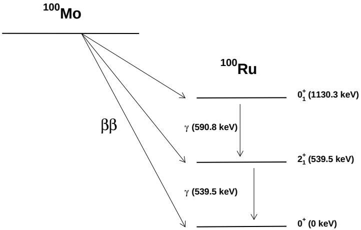


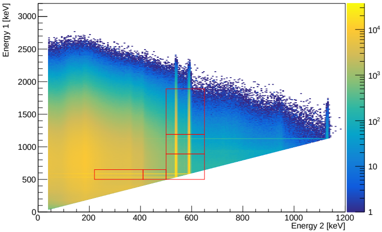


Excited states

- Use full data to search for $2(0)\nu\beta\beta$ decays to excited states
- $\beta\beta$ electrons are accompanied by γ quanta $\implies$ often reconstruct in **multi-crystal** events
- Search for distinct $\beta\beta - \gamma$ patterns in multi-crystal energies
- Simultaneous Bayesian fit to all signatures (7 for $2\nu\beta\beta$, 17 for $0\nu\beta\beta$)



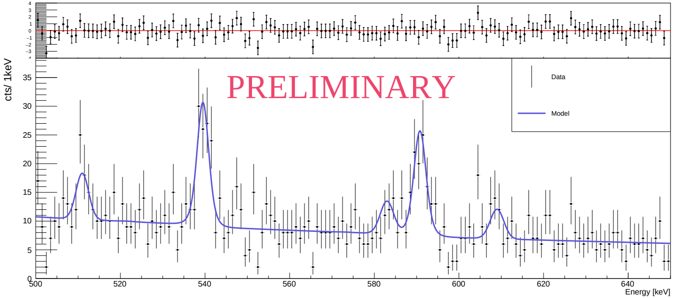




Excited states cont.

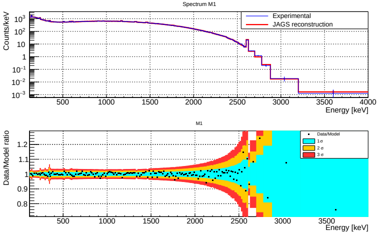
- Fit to unblinded data gives measurement of $2\nu\beta\beta$ to 0_1^+ and limits on other modes:

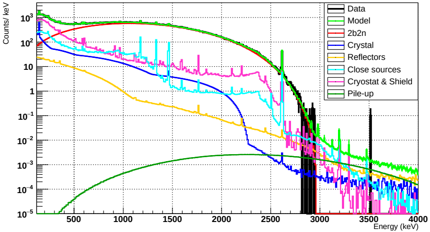
Mode	CUPID-Mo constraint	Previous leading constraint (NEMO-3)
$2\nu \rightarrow 0_1^+$	7.9 ± 0.9 (stat)$^{+0.2}_{-0.3}$ (syst) 10^{20} yr	7.5 ± 0.6 (stat) ± 0.6 (syst) 10^{20} yr
$2\nu \rightarrow 2_1^+$	$> 4.2 \times 10^{21}$ yr	$> 2.5 \times 10^{21}$ yr
$0\nu \rightarrow 0_1^+$	$> 1.1 \times 10^{23}$ yr	$> 8.9 \times 10^{22}$ yr
$0\nu \rightarrow 2_1^+$	$> 2.2 \times 10^{23}$ yr	$> 1.6 \times 10^{23}$ yr



Background model

- Construct a model of the experimental data
- Linear combination of MC simulated spectra (Geant4)
- Preliminary model of three data spectra:
  - $\mathcal{M}_{1,\gamma,\beta}$: Single crystal γ/β events
  - $\mathcal{M}_{1,\alpha}$: Single crystal α events
  - $\mathcal{M}_2$: Two crystal events - model summed energy
- Bayesian fit implemented with JAGS [4]
- Data well reproduced, enables several further physics studies

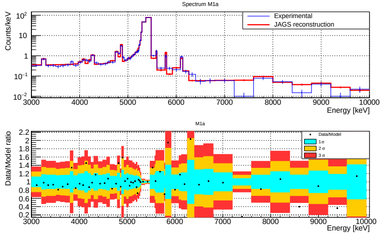




[4] Just Another Gibbs Sampler

Background model cont.

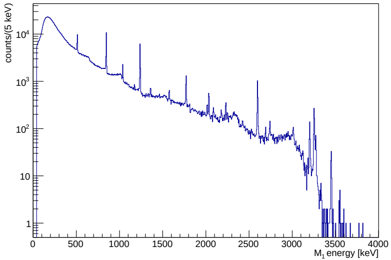
- Used to extract background index $b \sim 3 \times 10^{-3}$ $\mathrm{cts/keV/kg/yr}$
- Extract crystal contamination
- Use CUPID MC to convert to a predicted bkg index for CUPID

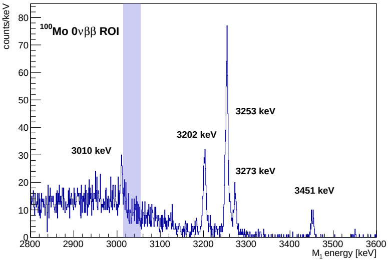


Component	Activity ^{226}Ra	Activity ^{228}Th	CUPID bkg index ^{226}Ra/^{228}Th [ckky]
Bulk	$< 0.3\ \mu\mathrm{Bq/kg}$	$0.3 \pm 0.1\ \mu\mathrm{Bq/kg}$	-/$(1.5 \pm 0.5) \times 10^{-6}$
Surface 10 nm	$1.2 \pm 0.6\ \mathrm{nBq/cm^2}$	$< 2.2\ \mathrm{nBq/cm^2}$	$(6 \pm 3) \times 10^{-6}$ / $< 9 \times 10^{-6}$

^{56}Co calibration

- Dedicated calibration measurements with ^{56}Co source performed
- Has several γ with $E > Q_{\beta\beta}$
- Studies on energy resolution beyond $Q_{\beta\beta}$ ongoing

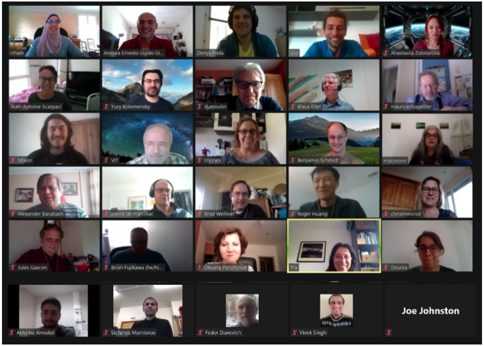




Conclusion

- CUPID-Mo successfully demonstrated LMO scintillating calorimters for CUPID
- Performance at or close to the CUPID goals
- But was also an important experiment in its own right
- New $0\nu\beta\beta$ (to ground and excited states) results
- Robust background model informing the CUPID design
- Other interesting analyses nearing completion!

Thank you!
Stay tuned for more results from CUPID-Mo!



Backup